Enhanced Ocean Predictability Through Optimal Observing Strategies

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LONG-TERM GOALS

The long-term goal of this research is to develop the requisite technologies for effective observation strategies that provide the best possible now-casts and forecasts of oceanic conditions. This research contributes to the effort to predict mesoscale and submesoscale conditions and to understand the physical processes responsible for these conditions.

OBJECTIVES

There were three tightly integrated objectives. The first was to focus both oceanographic and dynamical systems approaches on developing optimal observing strategies. The common thread linking both approaches was Lagrangian analysis, and so the first phase of the work addressed the question of how best to utilize Eulerian current maps constructed from disparate data and how to use the information contained therein to design optimal observing systems.

The second objective was to design an optimal observing strategy from a synthetic database. Here we used primitive equation model simulations as the control. The last objective was to apply this technology to the Gulf of Mexico where both high-resolution numerical model results and drifter data were available.

APPROACH

We approached the objectives in this effort by combining the oceanographic methodology of objective Eulerian current reconstruction initiated by Rao and Schwab (1981), Eremeev et al. (1992) and Chao et al. (1998) with dynamical systems techniques of invariant manifold calculations as presented in Poje and Haller (1999). During the first phase of the study, we utilized model flows where the Lagrangian dynamics are known. Analysis methodologies developed from prior ONR supported research were

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14. ABSTRACT
The long-term goal of this research is to develop the requisite technologies for effective observation strategies that provide the best possible now-casts and forecasts of oceanic conditions. This research contributes to the effort to predict mesoscale and submesoscale conditions and to understand the physical processes responsible for these conditions.

15. SUBJECT TERMS

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applied to flows so as to establish benchmark cases for testing observation. The second phase was to apply the methodology in a natural oceanographic setting. Due to the availability of relevant data and model output, the Gulf of Mexico was used.

WORK COMPLETED

The emphasis during the first year was on the first objective. In fiscal year 1999, practical aspects involved in the reconstruction of Eulerian velocity fields from Lagrangian data were addressed. A major result was quantifying the effect drifter coverage (in particular data voids) has on the accuracy of the Eulerian velocity reconstruction. A reduced gravity, double gyre primitive equation model was used for that effort.

In the second year, progress was made on all three objectives. During fiscal year 2000, a deployment strategy that produced optimal dispersion was identified for the double gyre model, which represented significant progress on the first two objectives. Additionally, high resolution Gulf of Mexico model and drifter data were analyzed using both the dynamical systems and objective mapping methods, an essential element of the third objective.

Fiscal year 2001 was devoted to three main scientific questions. First, we verified that the optimal deployment strategy, when applied to the double gyre model, significantly reduces reconstruction error of the Eulerian velocity when compared to random deployments. Second, due to specific comments at the DRI meeting in Nice (2000), we investigated the effect stochastic wind forcing has on the Lagrangian analysis of ocean models. This directly impacts the optimal launch strategy for natural flows due to environmental uncertainty. Finally, we began constructing the Lagrangian analysis necessary for an optimal deployment in the Gulf of Mexico.

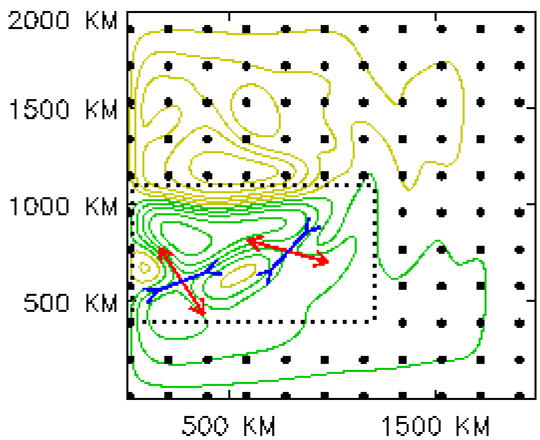
The optimal observation strategy involves identifying launch sites that achieve maximum dispersion, so as to improve drifter coverage. Fixed-time stagnation points, under the appropriate flow criteria, approximate these launch locations.

Analysis of the Gulf of Mexico model with drifter data involved two approaches. First, the objective mapping technique allowed the model and drifter data to be merged so as to improve the accuracy and predictability of numerical trajectories. Second, a finite time, invariant manifold technique from dynamical systems theory was used to delineate the boundaries of coherent structures.

RESULTS

The optimal drifter deployment involves identifying launch sites that achieve maximum dispersion, so as to improve drifter coverage. For the double gyre flow, fixed-time, hyperbolic stagnation points can approximate the maximum dispersion launch locations. However, the path that drifters take as they leave the hyperbolic region is along the outflowing manifold. We developed a time-dependent launch strategy whereby drifters are re-launched based on the magnitude of the local stretching rate. This stretching rate is estimated by computing the eigenvalues of the velocity gradient matrix evaluated at the launch site at the launch time. For example, if the positive eigenvalue at a particular launch time was 0.33 day^{-1}, a new drifter would be launched in three days to maintain uniform resolution along the outflowing manifold.

The model and sub-domain used for velocity reconstruction experiments are shown in Figure 1. Two hyperbolic stagnation points within the sub-domain formed the basis of the continual launch strategy. The drifter positions after 41 days of continual deployment sampled the outflowing manifolds (Figure 2).



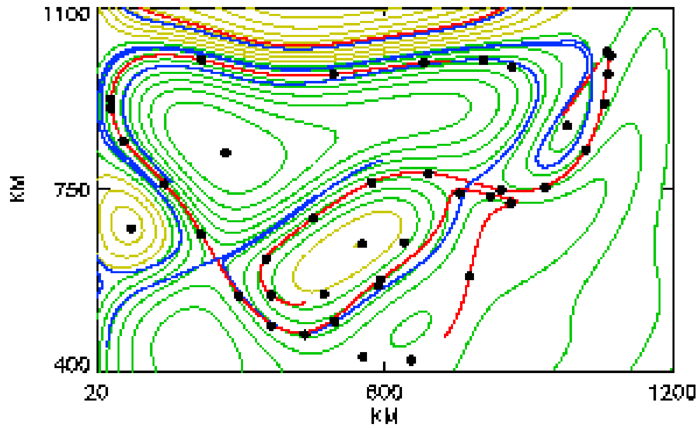
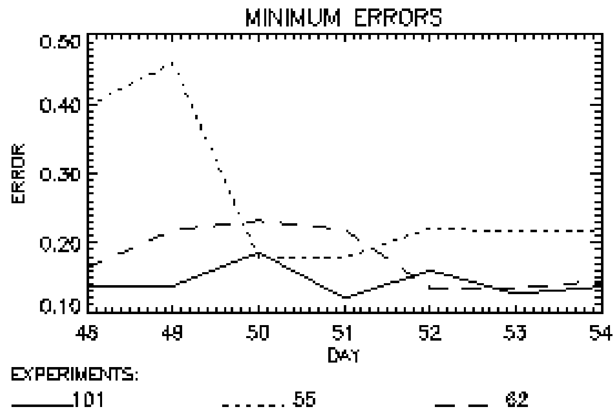


Figure 1. (left) Basin-scale (2000km by 2000km) double-gyre model and the 1200km by 700km sub-domain used for velocity reconstruction experiments south of the central jet. Two fixed-time hyperbolic stagnation points in the sub-domain are used to form the optimal continual release launch strategy. The region exterior to the sub-domain is uniformly sampled.

Figure 2. (right) The drifter deployment pattern that results from the continual-release strategy results in relatively uniform sampling of the outflowing manifolds. Thirty-six drifters are deployed in pairs along the outflowing direction of each saddle over 41 days, and the mean re-deployment time is 4.5 days. Four additional drifters are deployed in the eddy centers to fill data voids.

For comparison, 100 random deployment experiments were conducted. In these experiments, the velocity reconstruction error was used as a quality of deployment metric. Time series of the reconstruction error (Figure 3) for the three experiments with the minimum error during the nine days after the final launch shows that the directed launch strategy, Experiment 101, achieves consistently low error throughout the time period. A histogram of the reconstruction error (Figure 4) for all 101 experiments shows the mean value of 0.38 to be three times the value for the directed launch of 0.12.

Stochastic wind forcing of both a channel flow with a topographically induced eddy and a rectangular domain, reduced gravity Gulf of Mexico model with Loop Current eddy shedding indicate that the manifold structure emanating from hyperbolic regions is robust. Manifold averaging was performed and the mean manifold structure is consistent with the unperturbed flow.



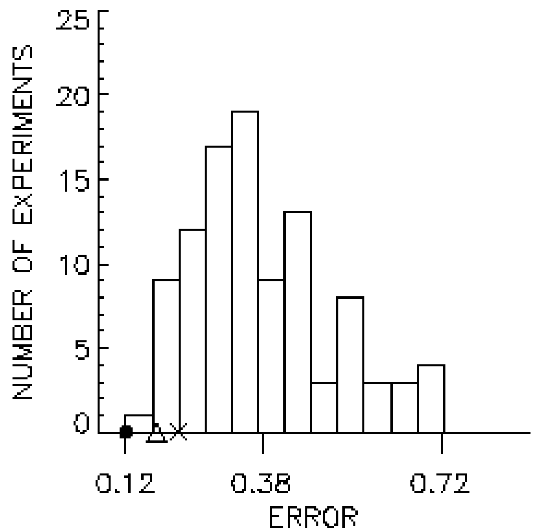


Figure 3. (left) Time series of reconstruction error for three (out of 101) experiments for six days after the last deployment. The optimal launch strategy, Experiment 101, maintains low error while the other two minimum error experiments vary significantly.

Figure 4. (right) A histogram of all 101 experiments shows that the directed deployment, with minimum error of 0.12, is reduced by a factor of three from the mean value of 0.38. The maximum error of the 101 experiments was 0.72.

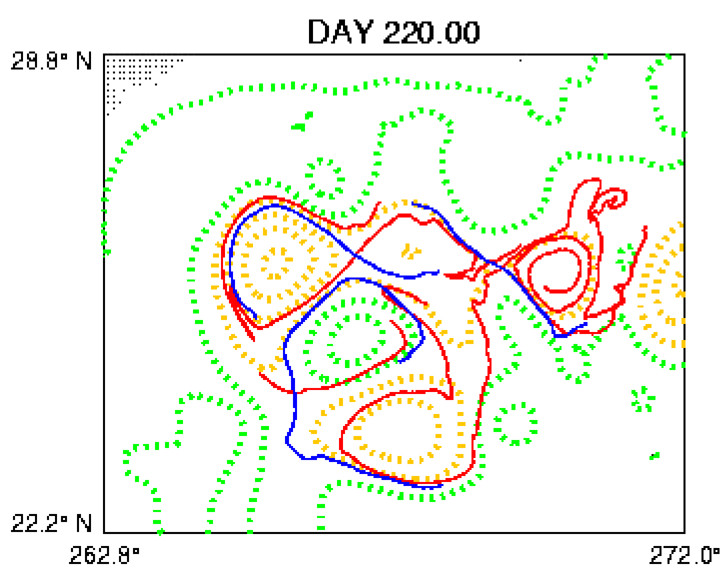


Figure 5. Mainfolds generated for the Gulf of Mexico model flow from three hyperbolic regions. The top left corner is the Texas coast. The large Loop Current ring in the northwest is de-training to the adjacent anticyclone.

An application was made to the Gulf of Mexico to study the how the manifold structure in a natural setting compares to the idealized model results. The fixed-time stagnation points of the height field in the Gulf of Mexico model were not easily to track due to inherent high frequency variability that does not exist in the double gyre flow. Nevertheless, we were able to generate robust manifold calculations that will be used for optimal deployment experiments.

Figure 5 shows Lagrangian structure of Loop Current rings and a cyclone in the western Gulf as delineated by three sets of manifolds. We used relative dispersion calculations to locate the hyperbolic regions. The optimal deployment algorithm applied to the Gulf of Mexico model data will require us to track the evolution of the hyperbolic regions and perform velocity reconstruction experiments similar to those described in Figures 1-4.

IMPACT/APPLICATIONS

The immediate application of this technology will be to Rapid Environmental Assessment (REA). In addition to the traditional military interest in REA, civilian applications in environmental crisis management, for example hazardous waste operations and pollution monitoring and containment, will increase substantially in the next few years.

Additionally, we see a direct application to both model assessment and data assimilation. Lagrangian data has not been used extensively to compare with model results due to limited comparison methods available. The manifold technique provides a new way to reconcile Eulerian and Lagrangian aspects of the flow by analyzing the relation of the drifter paths to the advective boundaries computed from the model. Assimilation of Lagrangian data suffers from the same limitation of available methods. By blending drifter data with model output, we significantly improved the ability to predict drifter trajectories with the blended Eulerian field.

Results obtained thus far are generic in that the spatial coverage and comparative quality issues of the Lagrangian data apply to open and arbitrarily shaped domains. Our results on dispersion in the double gyre and coherent structures in the Gulf of Mexico are applicable to all regions in the world ocean.

TRANSITIONS

The methodology in this study will be used to further assess the predictive capability of a high resolution Princeton Ocean Model (POM) of the Gulf of Mexico in a collaborative effort with Lakshmi Kantha at the University of Colorado. Additionally, this methodology was used in a masters thesis by Elias Hunter titled, “Advective Transport on the Louisiana-Texas Shelf,” at The University of Delaware. This effort was an extension of the work done by LCDR William Schultz where MODAS was used in combination with NMA to provide nowcasts of the Texas-Louisiana Shelf with drifter and mooring data.

RELATED PROJECTS

The nowcast technology is being utilized to investigate HF radar data, provided by Jeff Paduan at the Naval Postgraduate School, in Monterey, CA through another ONR project, N00014-00-1-0067.

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